

Performance Estimation of Supercritical CO₂ Cycle for the PG-SFR application with Heat Sink Temperature Variation

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1. Introduction

As a part of Prototype Generation IV Sodium-cooled Fast Reactor (PG-SFR) development, the Supercritical CO₂ cycle (S-CO₂) is considered as one of the promising candidates that can potentially replace the steam Rankine cycle. S-CO₂ cycle can achieve distinctively high efficiency compared to other Brayton cycles and even competitive performance to the steam Rankine cycle under the mild turbine inlet temperature region. In addition, mild sodium-CO₂ reaction can be substituted for violent sodium-water reaction to improve the reactor safety.

Previous studies explored the optimum size of the S-CO₂ cycle considering component designs including

turbomachinery, heat exchangers and pipes [1-3]. Among them, 75MWe S-CO₂ cycle has been selected and the system concept and design parameters are shown in Fig. 1 and Table 1, respectively.

Based on the preliminary design, the thermal efficiency is 31.5% when CO₂ is sufficiently cooled to the design temperature [1]. However, the S-CO₂ compressor performance is highly influenced by the inlet temperature and the compressor inlet temperature can be changed when the heat sink temperature, in this case sea water temperature varies. To estimate the S-CO₂ cycle performance of PG-SFR in the various regions, a quasi-static system analysis code for S-CO₂ cycle is developed by the KAIST research team.

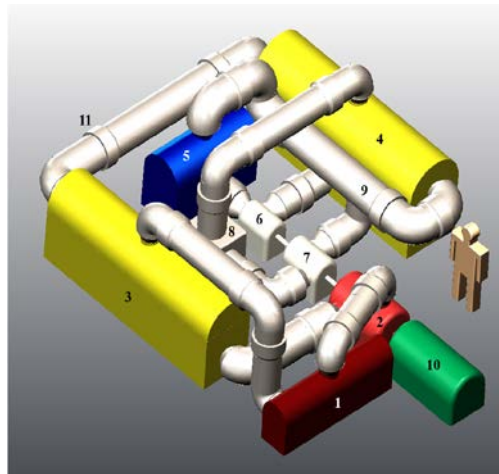


Fig. 1. The module of S-CO₂ cycle for the SFR application

Table I. The design parameters of S-CO₂ cycle for the SFR application

Thermal power, MW _{th}	76.5	Turbine inlet temperature, °C	508.4
CO ₂ mass flow rate, kg/s	606.1	Compressor inlet temperature, °C	31.3
S-CO ₂ cycle layout	Recompression	Turbine / MC / RC isentropic efficiency, %	92.5 / 88.2 / 91.1
Thermal efficiency, %	44.6	HTR / LTR effectiveness, %	95 / 95
Heat exchanger total pressure drops, %	5.5	Turbomachinery rotating speed, RPM	7,200
Compressor inlet / outlet pressure, MPa	7.5 / 20.2	Heat exchanger total volume, m ³	0.91

2. Off-design performance of S-CO₂ turbomachinery

To estimate the off-design performance of S-CO₂ turbomachineries, KAIST-TMD, 1-D mean line

turbomachinery design code developed by KAIST research team was utilized [4]. The off-design performance of S-CO₂ turbomachineries are utilized for the quasi-static system analysis code evaluation. Based

on the design parameters of S-CO₂ turbomachinery, the off-design performance of S-CO₂ compressor and turbine is estimated as shown in Fig. 2. To utilize the off-design performance map for the system analysis, the equivalent mass flow indicates the off-design performance for various operating conditions. The equivalent mass flow (\hat{m}) is defined as below.

$$\dot{m}_{eq} = \dot{m} \frac{\sqrt{\theta}}{\delta} \varepsilon \quad (1)$$

$$\theta = \left[\frac{\frac{\gamma_a}{\gamma_a + 1} T_a}{\frac{\gamma_{ref}}{\gamma_{ref} + 1} T_{ref}} \right]^2 \quad (2)$$

$$\delta = \frac{P_a}{P_{ref}} \quad (3)$$

$$\varepsilon = \frac{\gamma_{ref} \left(\frac{2}{\gamma_{ref} + 1} \right)^{\frac{\gamma_{ref}}{\gamma_{ref} - 1}}}{\gamma_a \left(\frac{2}{\gamma_a + 1} \right)^{\frac{\gamma_a}{\gamma_a - 1}}} \quad (4)$$

where \dot{m} , γ , P, T are mass flow rate, specific heat ratio, pressure and temperature, respectively.

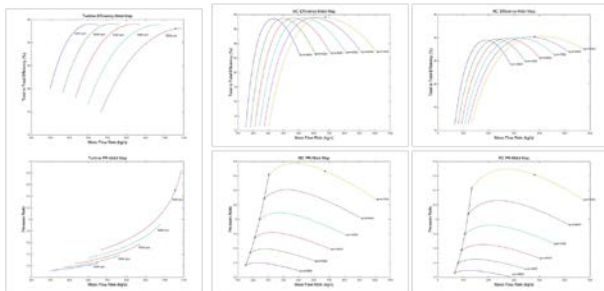


Fig. 2. Off-design performance of S-CO₂ turbomachinery

3. Quasi-static system analysis code

With the preliminary component design and performance parameters, a quasi-static system code is developed and its algorithm is shown in Fig. 3. The thermal efficiencies are predicted for varying heat sink temperature as shown in Fig. 4. From the annual database of sea water temperature history in East sea region, the maximum and the minimum temperatures are 23.8 and 7.4 degree celcius, respectively. As the compressor inlet temperature increases, the net power decreases due to pumping power increase to maintain the compressor inlet temperature. An abrupt decrease in

thermal efficiency is shown when the heat sink temperature reaches 23.8°C.

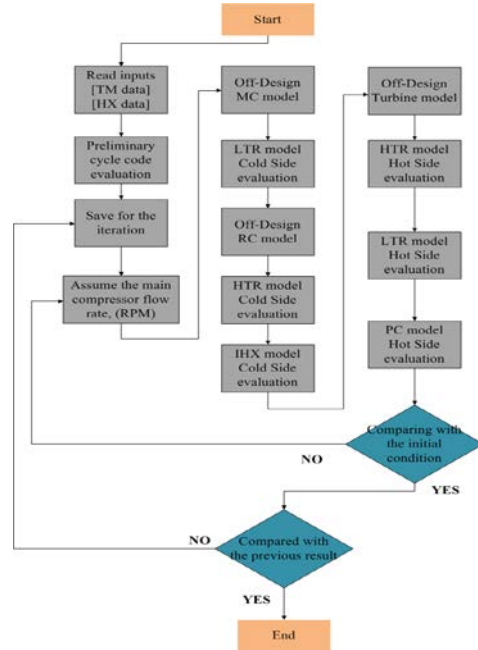


Fig. 3. a quasi-static analysis code algorithm

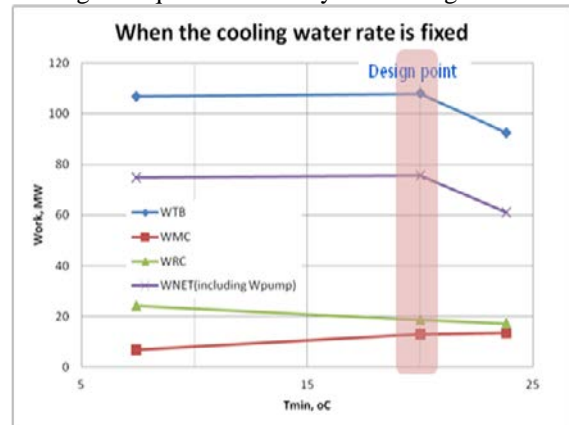


Fig. 4. Thermal efficiency of S-CO₂ cycle with the compressor inlet temperature variation

4. Summary and further works

A S-CO₂ cycle for PG-SFR is designed and assessed for off-design operation while the heat sink temperature varies. The heat sink temperature conditions are referred from the annual database of sea water temperature in East sea. When the heat sink temperature increases, the compressor inlet temperature can be influenced and the sudden power decrease can happen due to large water pumping power consumption.

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